UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

MASTER COPY - FOR REPRODUCTION PURPOSES

(2)

REPORT DOCUMENTATION PAGE

AD-A211 416

1b. RESTRICTIVE MARKINGS

3. DISTRIBUTION/AVAILABILITY OF REPORT
Approved for public release; distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S)
ARO 26007.1-EG-SBI

6a. NAME OF PERFORMING ORGANIZATION
Precision Acoustic Devices, Inc

6b. OFFICE SYMBOL *(If applicable)*

7a. NAME OF MONITORING ORGANIZATION
U. S. Army Research Office

6c. ADDRESS *(City, State, and ZIP Code)*
Freemont, CA 94539

7b. ADDRESS *(City, State, and ZIP Code)*
P. O. Box 12211
Research Triangle Park, NC 27709-2211

8a. NAME OF FUNDING/SPONSORING ORGANIZATION
U. S. Army Research Office

8b. OFFICE SYMBOL *(If applicable)*

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
DAAL03-88-C-0025

8c. ADDRESS *(City, State, and ZIP Code)*
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO

11. TITLE *(Include Security Classification)*
An Air Coupled Transmission Mode Acoustic Microscope for On-Line Non-Destructive Evaluation

12. PERSONAL AUTHOR(S)
John D. Fraser

13a. TYPE OF REPORT
Final

13b. TIME COVERED
FROM 9/1/88 TO 2/28/89

14. DATE OF REPORT *(Year, Month, Day)*
August 1989

15. PAGE COUNT
16

16. SUPPLEMENTARY NOTATION
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
Transducers, Imaging, Laminates, Graphite-Epoxy Laminates, Acoustic Impedance, Acoustic Microscope

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

Experiments were begun on imaging in transmission mode with two transducers. It has been possible to transmit and receive over distances of up to 8 inches in air. Although no actual imaging was done with the air transducers, the measured signal to noise ratio demonstrates that there is sufficient dynamic range to provide useful images of graphite-epoxy laminates. A material with close to the correct acoustic impedance for quarter wave matching to air has been made, and further process development will improve its uniformity. Although the development of a more optimum quarter wave material was not completed during this project, the feasibility of producing such materials has been demonstrated.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT
☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL

22b. TELEPHONE *(Include Area Code)*

22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

ARO 26007.1-EG-SBI

SUMMARY

Ultrasonic NDE systems suffer a major difficulty which prevents their use in many interesting applications. This is the necessity for providing a liquid coupling to the sample being inspected. This prevents the use of these systems in very hot environments, or where the materials being processed cannot be contaminated with water or other liquids. We have demonstrated the feasibility of using a transmission type ultrasonic microscope operating in air in the 1 MHz frequency range to address some of these applications. Such systems can be used for in-process evaluation of many structural materials such as composites and green ceramics.

Specialized ultrasonic transducers were built that are coupled to air using low acoustic impedance quarter wave plates made of silicone rubber. The feasibility of manufacturing more optimum materials for quarter wave matching was demonstrated. These transducers were capable of being driven at high voltage levels (1500 V) for highest possible transmission efficiency. The minimum insertion loss of these devices is 48 dB, and the 6 dB bandwidth is 6%.

Driver electronics were built which generate a 0.5 microsecond (us) wide, 1200 V double pulse. The second pulse was 5% lower in amplitude. A receiver was built with 6 dB noise figure and 20% bandwidth.

With these transducers, driving electronics, and receiver, we transmitted and received signals through air and a 3 mm graphite-epoxy aircraft part. These signals correspond to a transmission loss of 29 dB for the graphite-epoxy plate and its interfaces to air, and an overall signal to noise ratio of 11 dB for the received signal through the plate.

Additional improvements to the transducer efficiency and electronic S/N should add at least twenty (20) dB to the signal to noise ratio. This means that in graphite-epoxy or materials of similarly low impedance, such as fiberglass, rubber, plastics, or green ceramics, images of transmission loss can be made with more than 30 dB of dynamic range. Our prior experience in NDE imaging indicates that this is adequate for high quality inspection work.

FINAL REPORT

Ultrasonic NDE systems suffer a major difficulty which prevents their use in many interesting applications. This is the necessity for providing a liquid coupling to the sample being inspected. This prevents the use of these systems in very hot environments, or where the materials being processed cannot be contaminated with water or other liquids. We proposed to use a transmission type ultrasonic microscope operating in air in the 1 MHz frequency range to address these applications. We see such a system in use for in-process evaluation of many structural materials such as composites and green ceramics.

The key to these systems is the design and construction of highly efficient air-coupled transducers and appropriate driving and receiving electronics. We proposed to produce more efficient and broadband ultrasonic transducers for operation in air than has been previously done. These devices can have an insertion loss approaching 35 dB, similar to that of many standard ultrasonic search units.

The results obtained from this research may lead to a practical system for detection of flaws ultrasonically without using liquid coupling. This could lead to improved in-process NDE of structural materials for use in many commercial products. Precision Acoustic Devices (PAD) sees an opportunity for a scanned ultrasonic microscopy technique for a larger variety of in-process applications.

We have collaborated with Prof. B. T. Khuri-Yakub of Stanford University who has experience in making air transducers in the frequency range of interest and, who is presently investigating the use of novel porous (> 90% porosity) quarter-wave matching materials for making broadband and efficient ultrasonic air transducers. Prof. Khuri-Yakub's interests are in inspecting green ceramics. Also, Prof. Khuri-Yakub holds the patent on the low frequency acoustic microscope, which has been licensed by PAD.

Precision Acoustic Devices intends to make this type of equipment available for sale to material manufacturers for process control applications. We expect the devices to be applicable to many structural materials.

Technical Objectives of Phase I

PAD has designed and constructed several 1 MHz ultrasonic air transducers and associated driving and receiving electronics. The technical objectives were as follows:

1. Develop a design and build several focussed air transducers for operating in the 1 MHz frequency range. The transducers have a large F-number because of the strong velocity mismatch between air and most structural materials. The design of the transducer takes into consideration saturation of the piezoelectric material, which sets the limit on the maximum voltages that can be applied to the transducer. Also, develop low impedance matching materials such as silicone rubber and glass bubble mixtures. We aimed to obtain impedances in the range of about 0.3 MRayl, which allows us a good match from a piezoelectric ceramic into air.

2. Acquire a high voltage power supply to excite the transmitting transducer either in tone burst or broad band mode of operation. We needed a voltage of about 1000 V applied to the transducer in order to achieve the desired signal to noise ratio. Construct low noise receiver electronics to obtain the necessary sensitivity for detecting porosity variations and defects in the samples.

3. Modify a presently existing scanner and control electronics to generate preliminary images of samples such as composite materials, without immersing the samples in water.

4. Determine the practical limitations of such instruments in order to develop the criteria for the design and implementation of a prototype production line instrument for construction under Phase II funding.

QUARTER WAVE PLATES

The key to the successful design of efficient air-coupled transducers is the manufacture of very low impedance quarter-wave matching materials to couple sound energy from the high impedance ceramic (Z=34 MRayl) to air (Z=.0004 Mrayl). Experiments were performed with three classes of material: pure silicone rubber, microballoons in epoxy, and expandable microballoons in silicone rubber. The materials were cast into slugs, the acoustic properties measured, and processes examined for casting the materials into sheets of the proper quarter-wave thickness and bonding to the ceramic element.

Of primary interest are the expandable plastic microballoons (Expancel Company). It was hoped that we would be able to tailor the impedance of the matching materials by appropriately processing the microballoons in a silicone rubber matrix, thus achieving very low impedance composite mixtures. The first samples of the composite material were not very good.

One candidate material for the quarter-wave plate was manufactured successfully in November. This material was a mixture of glass microballoons in an epoxy matrix. Microballoons were added to epoxy until the mixture got to the consistency of bread dough. Then this mixture was outgassed and cured. Sample slugs were processed for characterization. This material was determined to have an impedance of 1.2 MRayl. While not ideal for the matching impedance desired, successful air transducers can be made from such a material (see Figure 1). This material has the benefit of being able to be easily processed into conformal quarter-wave plates using PAD's proprietary techniques. Silicone rubber has a similar acoustic impedance to this material. Therefore, the choice between these two materials will be made on ease of processing, and durability and stability over time.

Casting RTV in flat molds produced a consistent sample approximately .120" thick; the velocity was measured to be 1.01 mm/usec. A second sample was cast at a controlled thickness of .025"; its velocity was measured at 1.02, and its impedance at 1.0 MRayl.

It is desired to get materials that have even lower impedances than 1.2 MRayl. It is expected that Expancel microballoons in a silicone rubber matrix will have an impedance on the order of 0.3 MRayl. This will yield a cleaner transducer response than the higher impedance material (Figure 2). Additional samples of this material were made by casting the material between tightly clamped glass plates. This proved to be relatively successful, although several problems remain in casting layers of just the right thickness. Acoustically characterizing the material proved difficult.

Several samples of expanding microballoons in the RTV material were cast. The first sample, cast in a flat mold, was expanded but not consistent in texture. For the second sample the temperature was increased to 110 degrees C and the microballoon concentration was decreased to 10%, resulting in a consistent appearance throughout the material. However, the density of the sample was not uniform.

In an effort to deal with this nonuniformity and control the thickness of the sample, the next four samples were cast in metal molds. A thinner was used in varying amounts to make the RTV less viscous for impregnation purposes, and a range of temperatures was tried to control the microballoon expansion and RTV cure. The best results so far were obtained at 120 degrees C using 30% thinner. The velocity of this material was difficult to measure as it was very lossy, but is lower than the RTV alone. An improved measuring technique using air transducers will be required to accurately characterize this material.

Further work on casting this quarter-wave material to thickness is required. The main problem to be overcome is that the RTV cures at about the same time or before the microballoons expand. This results in a thicker sample than is desired. Because of this difficulty, pure RTV was selected to build the transducers.

TRANSDUCERS

During the initial months of the contract, the transducer design parameters were analyzed. Two models were identified as promising: a 1 MHz, half-inch diameter, 75 mm focal length with f-number of 6; and a 1 MHz, quarter-inch diameter, 26 mm focal length with f-number of 4. The focal lengths and apertures were chosen tc provide good resolution with short transit distance through air, for sensitivity. The large f-number in air is reduced to small f-number in solids, due to the large refraction that occurs because of the great difference in velocity between air and solid materials.

Also, a new ceramic material, EC-98 (EDO Western Company), was chosen for use as the piezoelectric element, because of its extremely high dielectric constant. This lowers the electrical input impedance of the finished device to a level that can be matched into the driving and receiving electronics. Orders were placed for this material, and the EC-98 ceramic was processed into spherical shells with the proper focus by PAD's in-house ceramic shop.

A new poling procedure was developed for the new high-dielectric constant ceramic chosen for this project. Coupling constants similar to those of typical PZT materials are being achieved.

After measurement of poled ceramic parameters, wires were attached to the ceramic. The ceramic was glued into a case using epoxy. Figure 3 shows details of the construction. A UHF connector was soldered to the leads. The RTV quarter wave plate was applied to the face of the transducer using the natural tackiness of the RTV for adhesion, and the transducer was taken to be tested.

Initial testing was performed by connecting the finished, untuned transducer, air loaded, to the high voltage pulser, set for two 0.5 microsecond pulses with 0.5 microsecond off time in between. A 10 kOhm resistor bled off DC charge buildup. The repetition rate was 100 Hz. The drive voltage was slowly raised in order to verify that the electrical connections and wiring were adequate for the anticipated operating conditions. The initial voltage was 500 V peak, and no failure was observed. As the voltage was raised past 750 volts, arcing developed across gaps which formed in the ground electrode. It was determined that the current carrying capacity of the electrode had been exceeded. New transducers were built with thicker electrodes.

Several air transducers were fabricated using thicker electrodes. This modification, together with higher current capacity in the leads and ground shield, have yielded transducers which have survived several hours with 1500 Volt pulse trains, of up to 20 pulses each, applied several hundred times per second.

The RTV rubber quarter wave plate formula was used for all transducers, as the microballoon material is not yet uniform enough to form accurate quarter wave plates.

Impedance plots shown in Figures 4 and 5 have indicated that the last two transducers fabricated, numbers 5 and 6, are behaving as expected. An experiment was performed to measure the round trip insertion loss of transducer number 5 with respect to frequency. The loss in air under the prevailing temperature and humidity conditions was estimated and subtracted, yielding the plot shown in Figure 6. The minimum insertion loss is 48 dB, and the 6 dB bandwidth is 6%. The insertion loss is higher than desired, because no tuning was used, and the quarter wave plate is lossy. However, it is low enough to be useful, as we shall show below.

ELECTRONICS

The driving electronics were designed around a driver board purchased from Directed Energy Corporation, which had been jointly developed for a medical customer.

Delivery of the driver board was taken, and a high-voltage safe layout of the driver electronics enclosure was completed. The board and power supplies were installed in the enclosure, and testing was performed.

Trigger circuitry was added to the enclosure, completing the driver electronics. We were able to generate a 0.5 microsecond (us) wide, 1200 V double pulse. The second pulse was 5% lower in amplitude. This input should be sufficient to drive the air-coupled transducers to generate images. It is also possible to generate longer pulse trains with a similar amount of drop per pulse, which gives a higher energy and a narrower bandwidth, better matching the transducer bandwidth.

Two receiver designs were implemented, the first with a commercial hybrid low noise amplifier, the second based on an in-house design using integrated circuits and aggressive band-limiting to minimize noise. The performance of the in-house design was by far the better.

RESULTS

Experiments have begun on imaging in transmission mode with two transducers. We have successfully transmitted and received over distances of up to 8 inches in air. We will be improving the noise performance of our receiving circuitry, and attempting to transmit and receive through a 1/8 inch plate of graphite-epoxy composite. This improvement will be conducted outside the scope of this contract on PAD's own account.

With the best transducers and receiver, we obtained the signals shown below in Figures 7, 8, and 9, representing received signals through air and a 3 mm graphite-epoxy aircraft part, as well as the receiver noise with no transmitted signal. These signals correspond to a transmission loss of 29 dB for the graphite-epoxy plate and its interfaces to air, and an overall signal to noise ratio of 11 dB for the received signal through the plate.

CONCLUSIONS

Although no actual imaging was done with the air transducers, the measured signal to noise ratio demonstrates that there is sufficient dynamic range to provide useful images of graphite-epoxy laminates. A material with close to the correct acoustic impedance for quarter wave matching to air has been made, and further process development will improve its uniformity. Although the development of a more optimum quarter wave material was not completed during this project, the feasibility of producing such material has been demonstrated.

Noise performance of the receiver can, in theory, be improved by about three (3) more dB. Taken together, these improvements should add at least twenty (20) dB to the signal to noise ratio. This means that in graphite-epoxy or materials of similarly low impedance, such as fiberglass, rubber, plastics, or green ceramics, images of transmission loss can be made with more than 30 dB of dynamic range. Our prior experience in NDE imaging indicates that this is adequate for high quality inspection work.

However, the additional reflection losses incurred would make imaging of higher impedance materials, such as glasses or metals, impossible. Only operation at much lower frequencies, where transducers could stand much higher applied power, and where the resolution would be poorer, could be done.

Therefore, we conclude that air transducer imaging of low impedance materials, such as rubbers, plastics, reinforced plastics, and green ceramics is feasible. We have demonstrated promising prototypes of air transducers and electronics to operate them. Some further work on the transducers is necessary to optimize them.

At this point, PAD feels that the amount of further work necessary to commercialize air transducers does not warrant a large Phase II development grant. The transducers and electronics developed require no additional effort to work with PAD's existing imaging systems. PAD intends to market the existing transducers and electronics, and continue improvements at its own expense. Also, PAD, as a subcontractor on a DOE contract soon to be let to Norton Company, and will be further developing and applying air transducers and electronics to evaluation of green ceramics as a part of that contract.

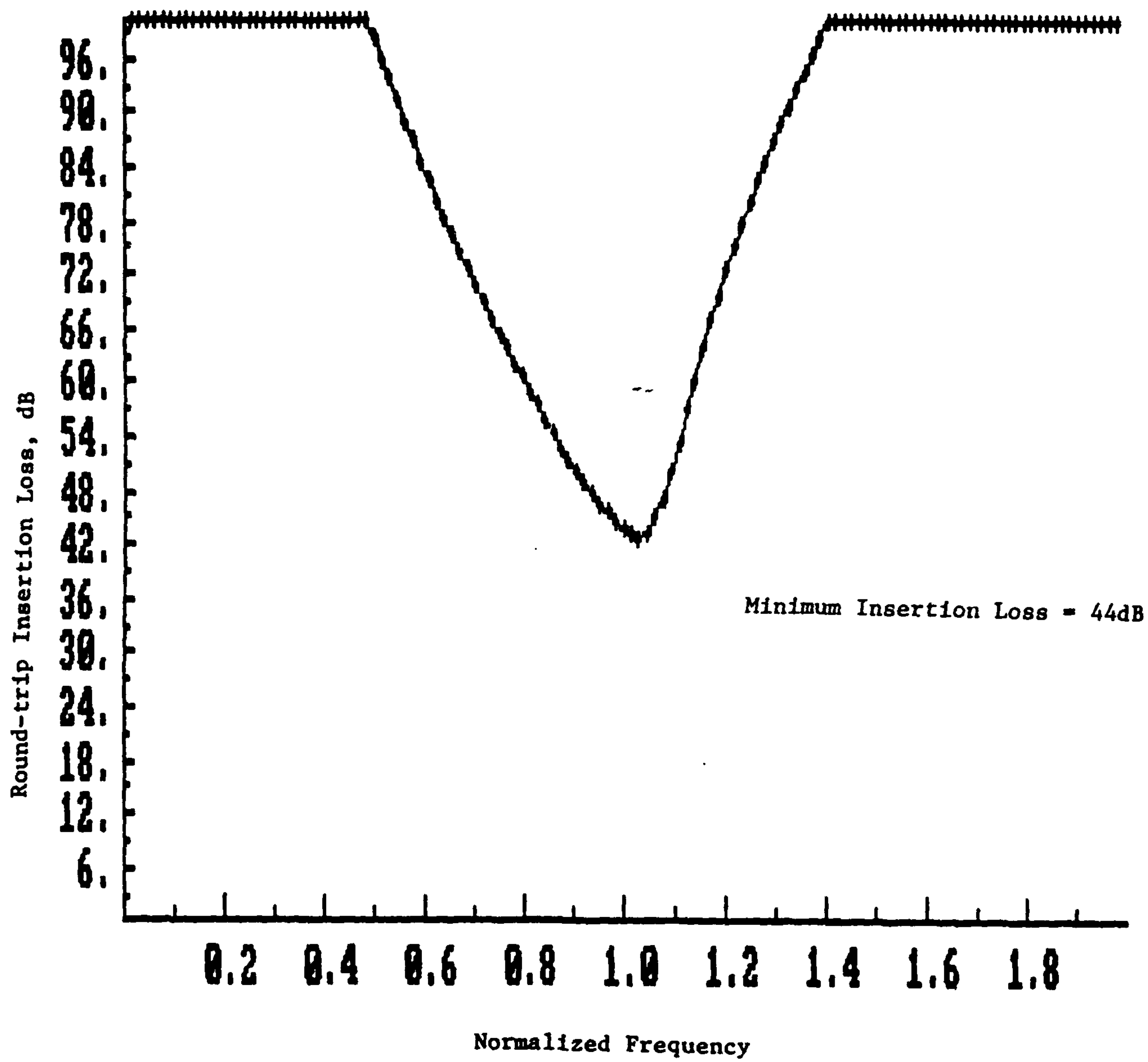

Figure 1. Frequency response of an air-coupled transducer with a Z = 1.2 MRayl quarter-wave plate.

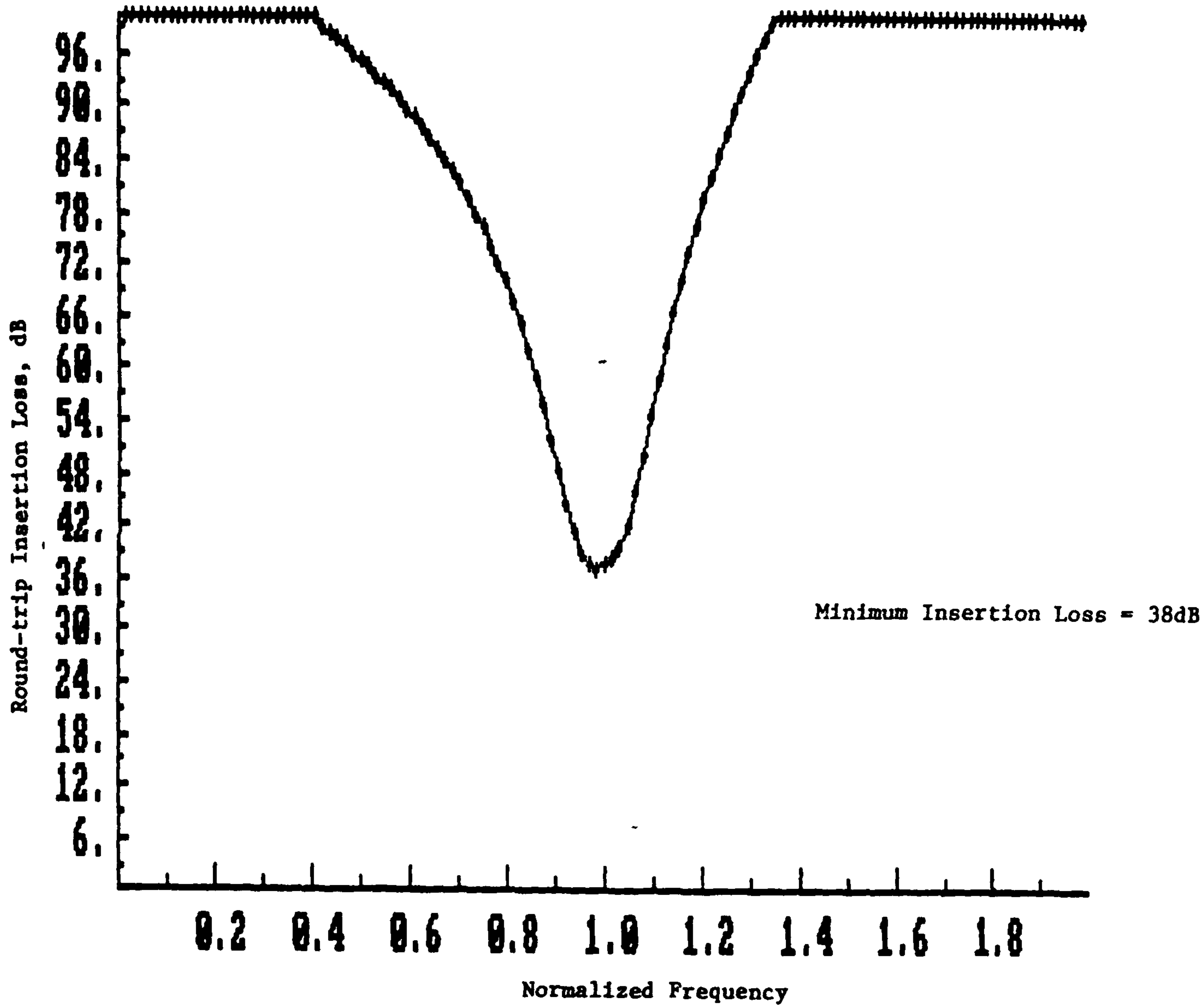

Figure 2. Frequency response of an air-coupled transducer with a Z = 0.3 MRay l quarter-wave plate.

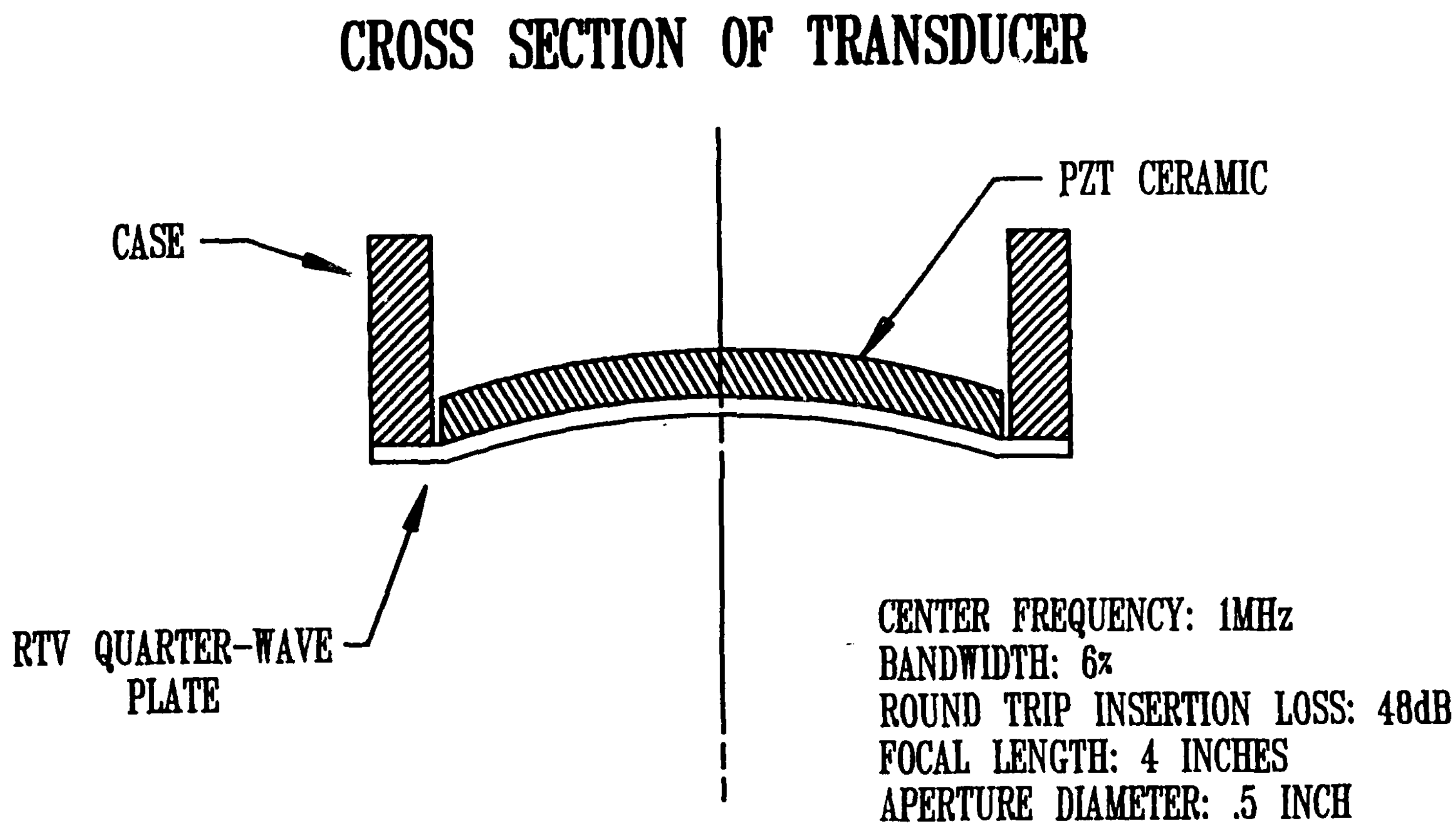

Figure 3. Design of Prototype Air Transducers.

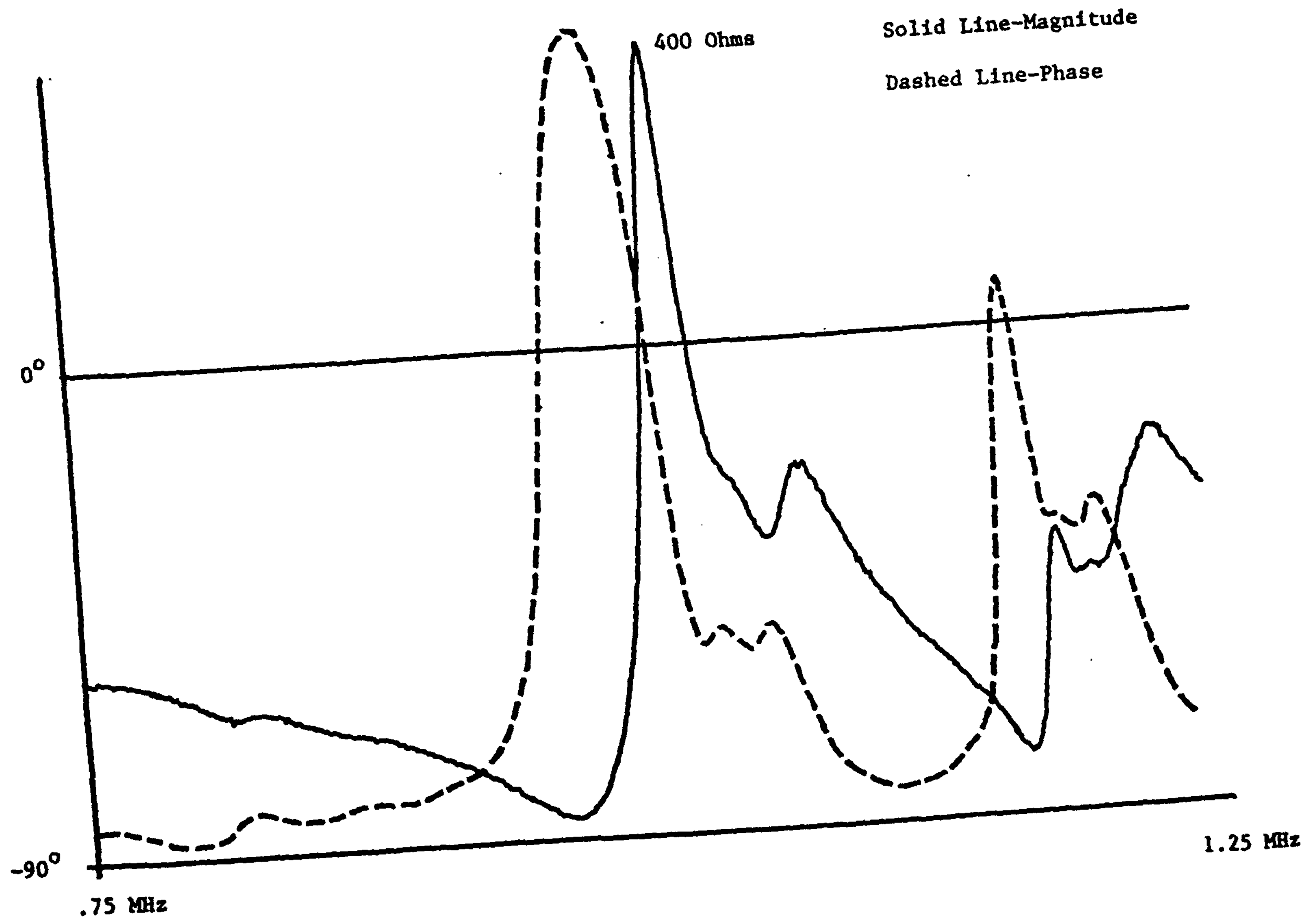

Figure 4. Electrical Impedance vs. Frequency Air Transducer #5.

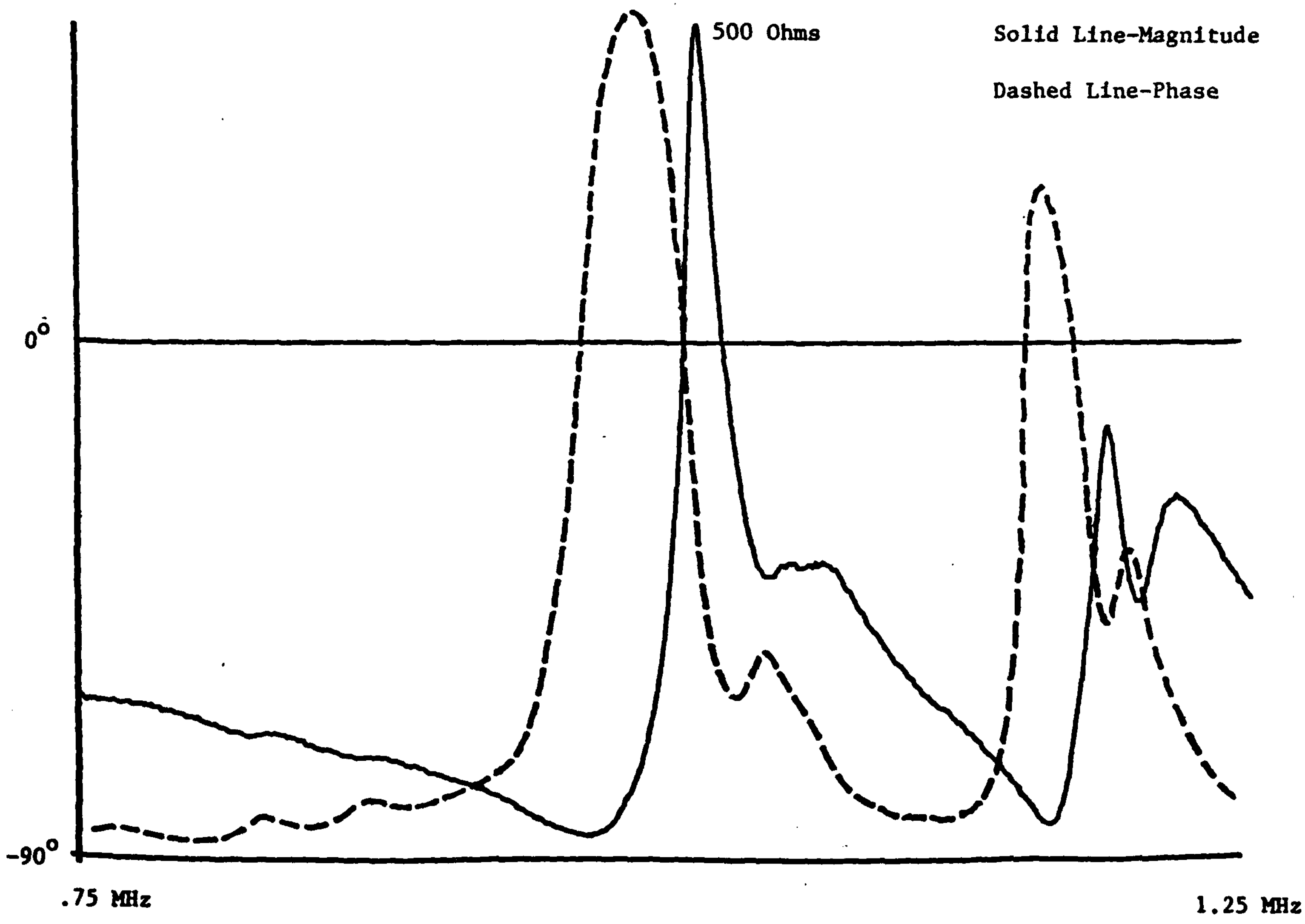

Figure 5. Electrical Impedance vs. Frequency Air Transducer #6.

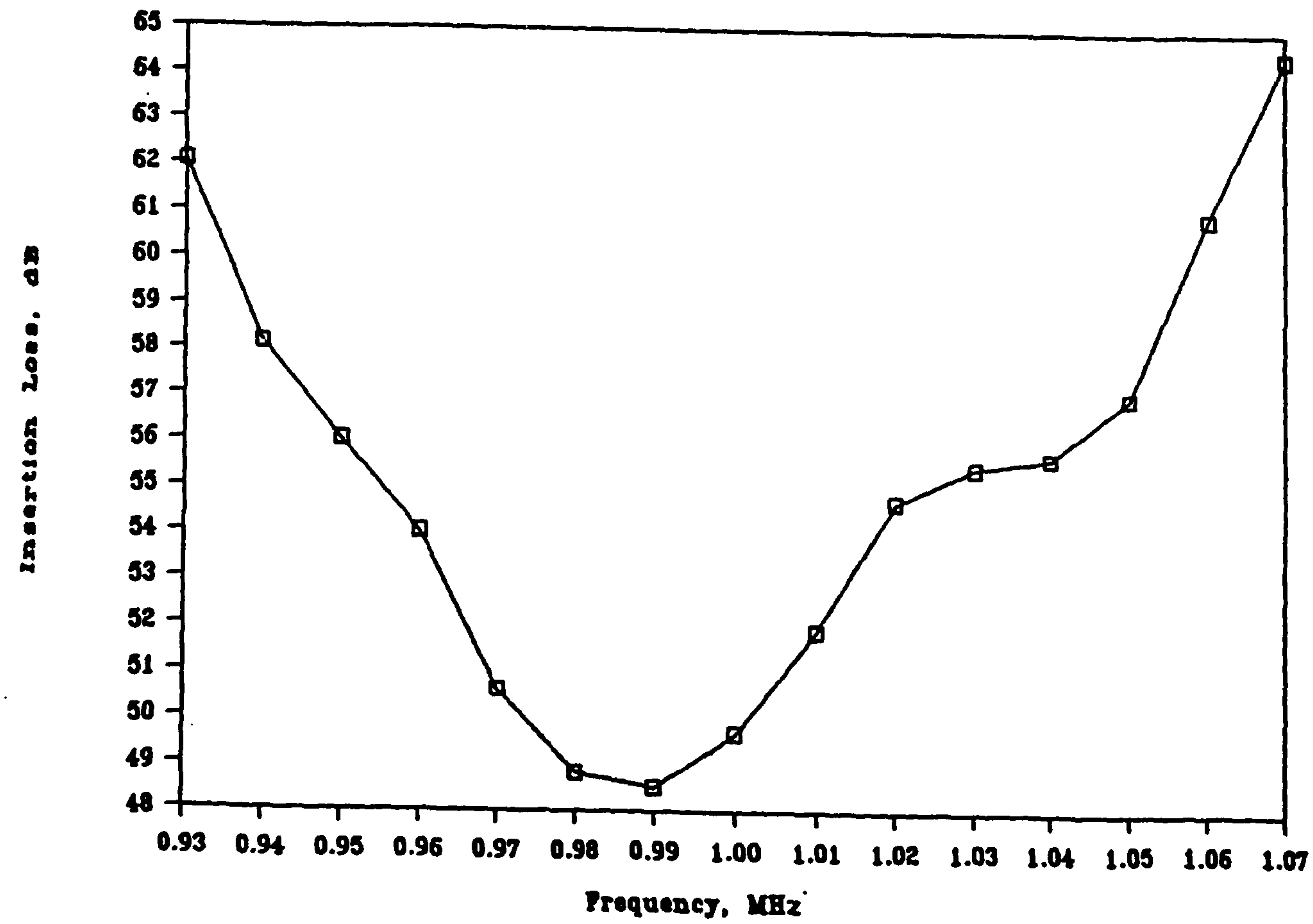

Figure 6. Insertion Loss vs. Frequency Air Transducer #5.

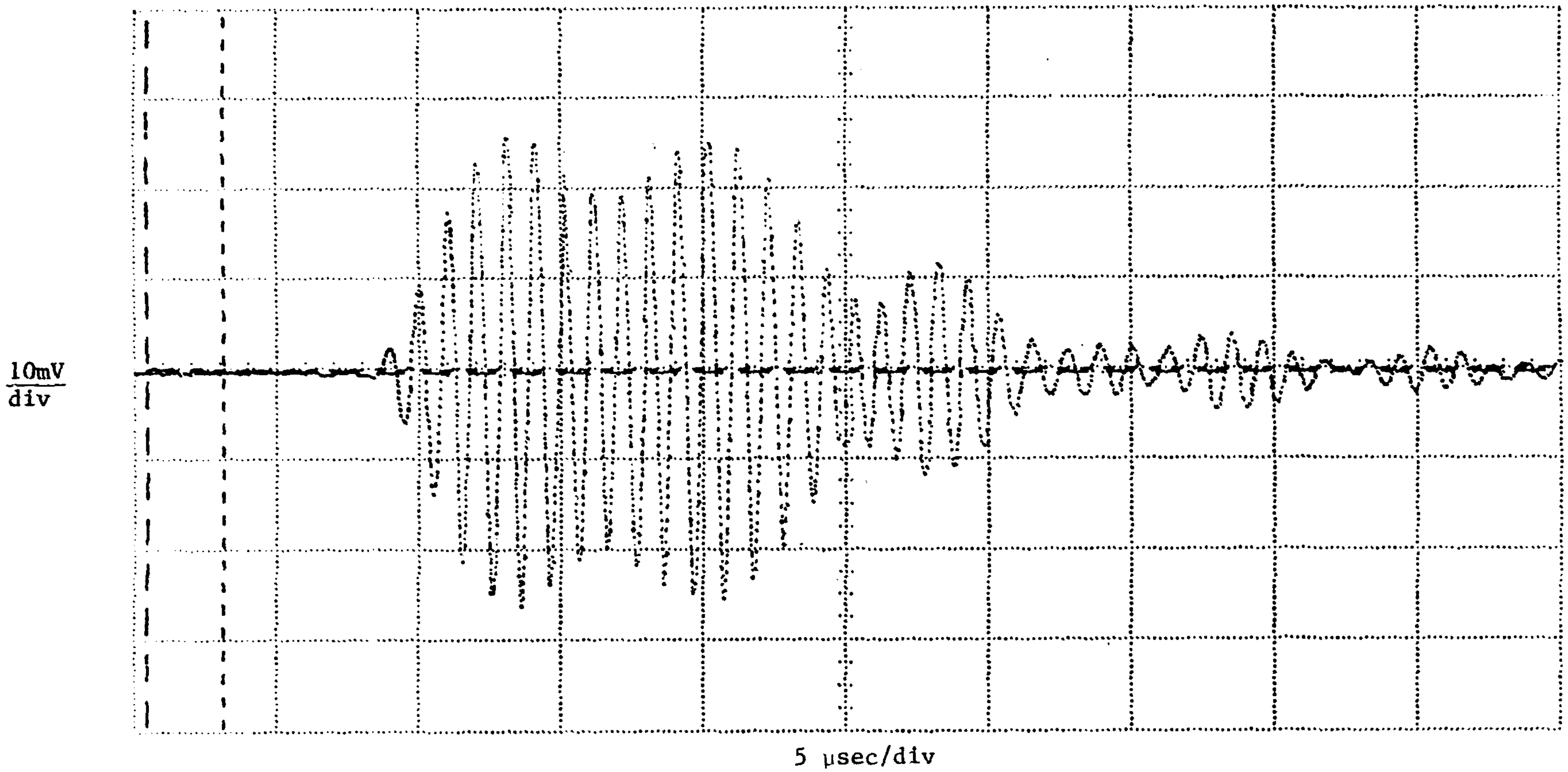

Figure 7. Received Signal Through Air; 16 mVRMS.

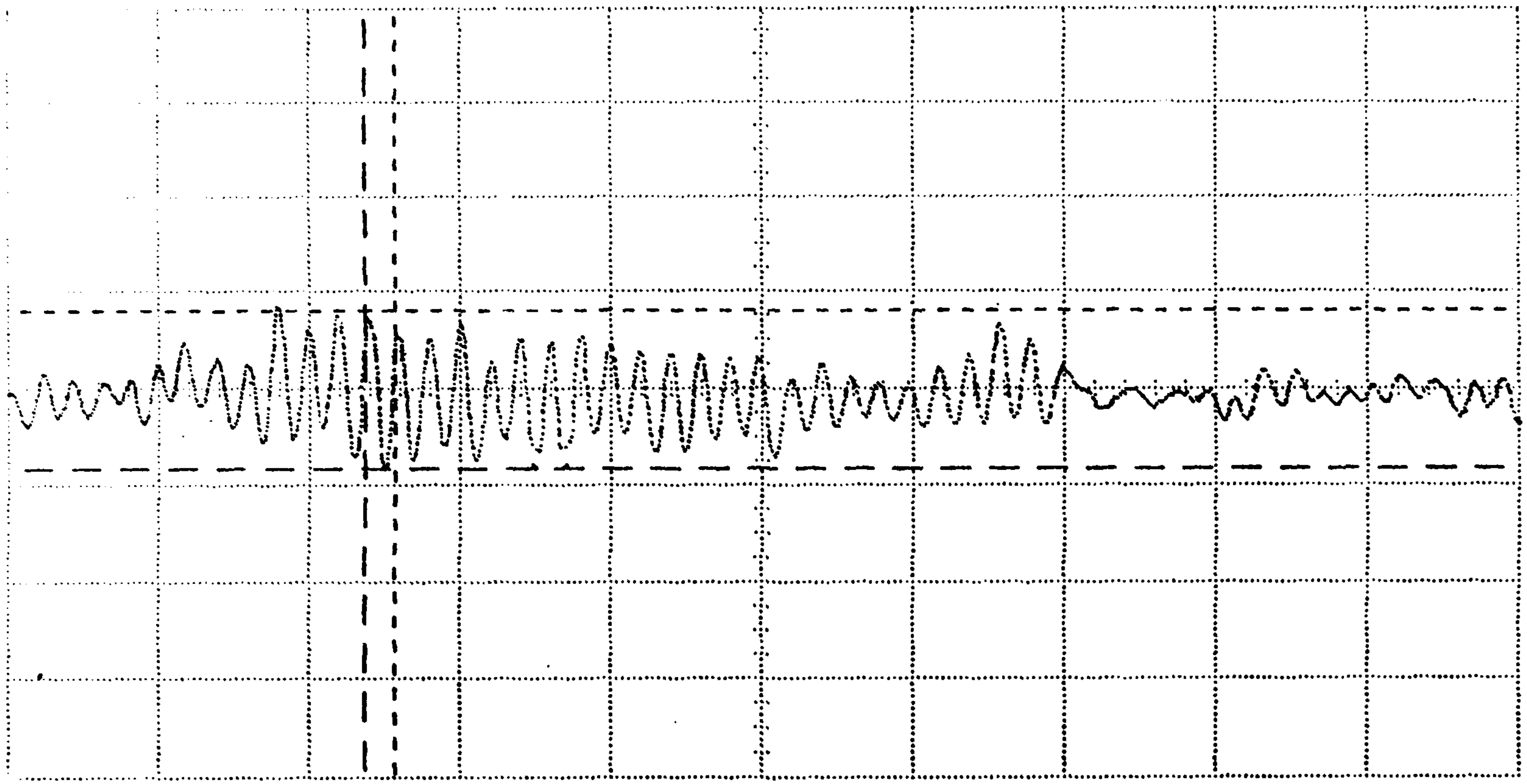

Figure 8. Received Signal Through Air and 3 mm Graphite-Epoxy Laminate; 555 μVRMS.

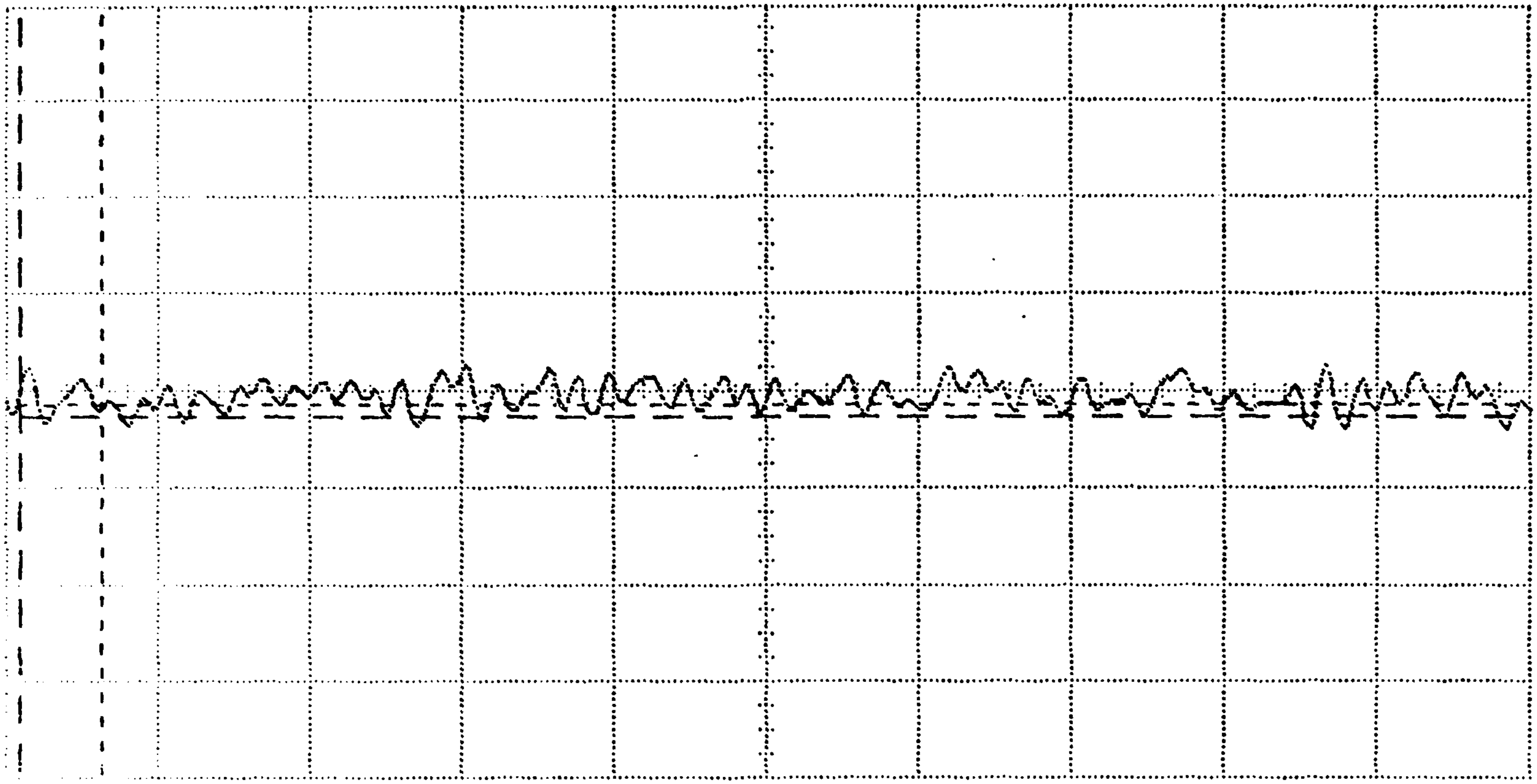

Figure 9. Receiver Noise, with no Signal Trasmitted; 150 μVRMS.